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PROTECTION OF EXPOSED PARTS OF SHELTERS AGAINST THERMAL RADIATION FROM MEGATON WEAPONS

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PROTECTION OF EXPOSED PARTS OF SHELTERS AGAINST THERMAL RADIATION FROM MEGATON WEAPONS

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Type C Final Report

by

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OBJECT OF TASK

To determine the effects of high-intensity thermal radiation resulting from the explosion of nuclear weapons on the exposed portions of certain defensive structures, and to propose protective measures.

ABSTRACT

In a theoretical study of the thermal radiation effects on underground shelters that are designed to withstand 100 psi, it has been found that for surface bursts of one megaton or greater the 100-psi contour is within the fireball. A 10-megaton weapon has been taken as an example and calculations have been made for the thermal flux received by a structure at a distance corresponding to the 100-psi overpressure. The total heat flux is of the order of 60,000 cal per cm^2. Possible measures for the protection of entrance coverings and ventilation valves are examined. Conventional heat-shielding materials seem to be impractical for these immense thermal radiation levels. The degree of protection necessary makes all but the most sophisticated materials impractical.

Simple carbon and graphite shields are discussed and more complicated shielding systems are proposed for future experimental studies.

STATEMENT OF THE PROBLEM

Nuclear weapons explosions described in the publication "The Effects of Nuclear Weapons"[1] indicate that the damage due to thermal radiation can be reduced manyfold by appropriate shielding. Also, sufficient shielding can be provided for survival against the ionizing radiation.[1,2] It is now apparent that survival in shelters is possible at a distance from the center of the explosion of megaton weapons that is even less than the maximum radius of the fireball, if protection of the exposed portions is provided against thermal radiation.

Figure 1 shows the time, temperature, and distance values expected from a 10-megaton surface burst. If one considers the comparable effects of nuclear weapons, he can calculate the radius of the fireball and the position of the 100-psi contour.[3,4] This is given in Figure 2 for weapons of various sizes. It can be seen that for bombs greater than 0.5 megaton, the pressure contour of 100 psi or more is within the fireball.

Shelters for the protection of people from blast damage and radioactive fallout are now being designed, with an overpressure criterion of 100 psi. The shelters are usually buried under six feet or more of earth for nuclear radiation protection. This depth of cover is more than adequate for the protection of the occupants from nuclear, thermal, and blast radiation, but the problem exists of protecting the exposed ventilation valves and entrance coverings so that they may operate as designed when subjected to very high thermal radiation levels.

APPROACH TO THE PROBLEM

Aluminum and steel are the proposed materials of construction for the valves and entrance coverings. These must be preserved from melting or other failure, and the mechanical functioning of the blast closure valves must be maintained.

Experiments in laboratories as well as at nuclear weapons test sites indicate that damage of exposed shelter appurtenances by thermal radiation can be minimized by the application of highly reflective coatings,[5] by the use of refractory materials to reduce heat conduction, and by use of coatings of materials with high latent heats of fusion and vaporization to serve as heat sinks.[6]

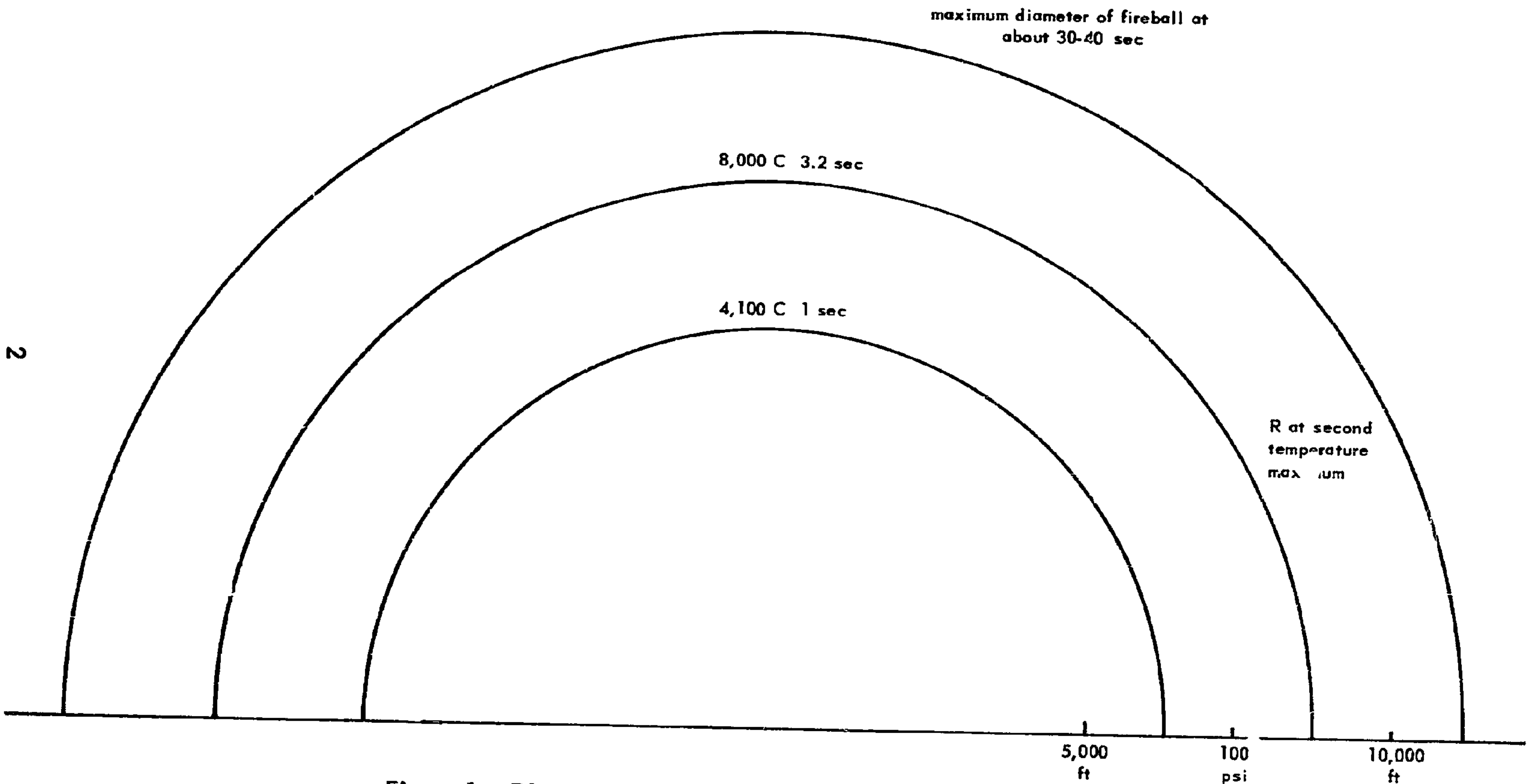

Figure 1. Distances, times, and temperatures for a 10-megaton weapon burst.

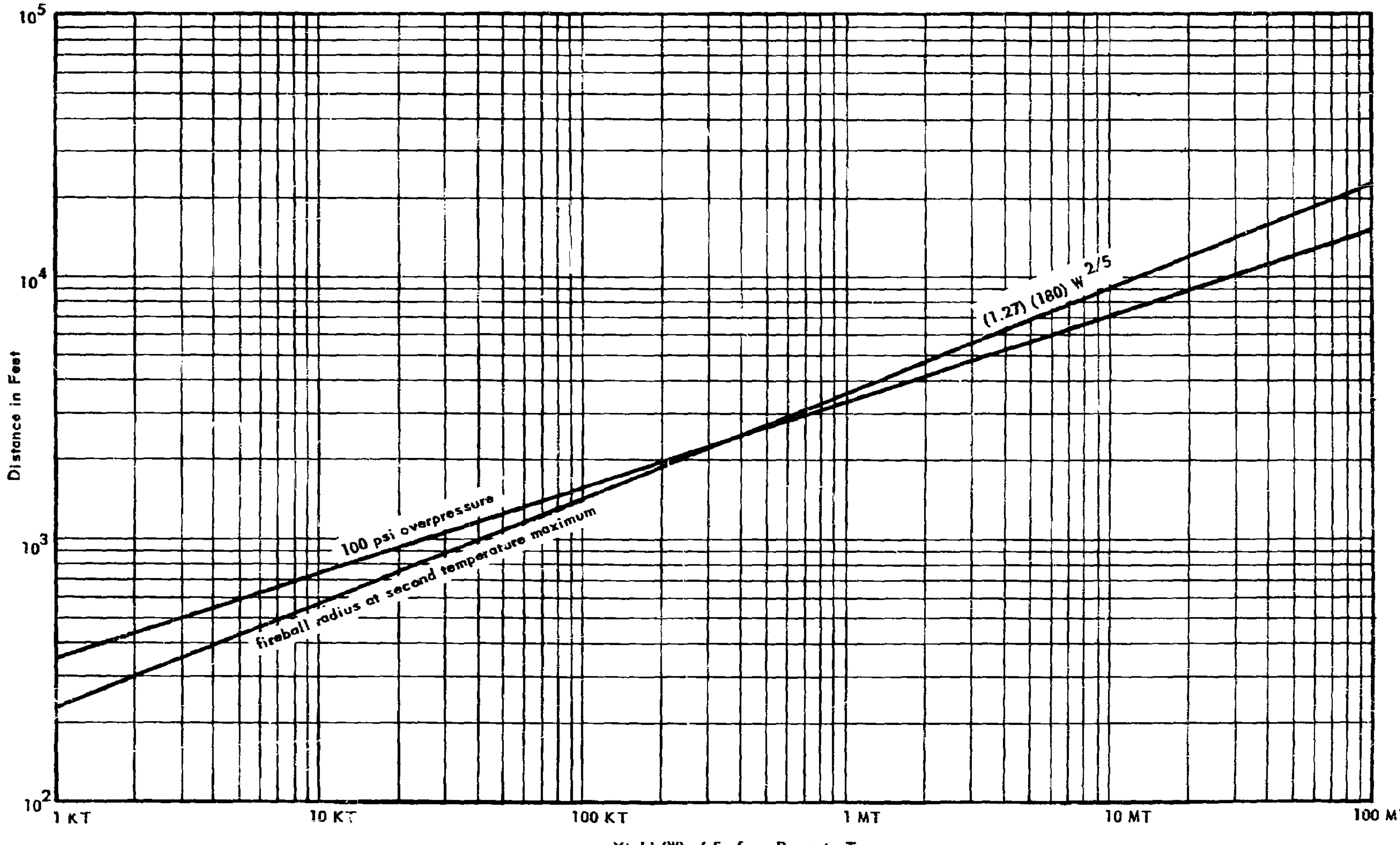

Figure 2. Thermal and pressure characteristics of nuclear weapons.

Much experimental work has been done on the thermal properties of materials for the nose cones of missiles and re-entry vehicles.[6,7,8,9,10,11] The specifications for these are different from the problem under investigation, because in addition to the high thermal fluxes, the nose cones are subject to supersonic wind velocities during their entire time of re-entry. H. A. King[8] has suggested six basic techniques that can be applied to the control of large heat fluxes such as those produced in the nose cones of missiles. They are:

Technique	Commonly Used Name
Conduction	1. Heat sink 2. Tubular
Convection	1. Transpiration cooling 2. Film cooling
Radiation	1. Radiation and/or reflection
Combination	1. Insulation 2. Ablation
Change of State	1. Physical 2. Chemical (endothermic reaction)
Electrical-Magnetic	1. Magnetohydrodynamic 2. Thermoelectric

The technique most suitable for heat shielding within the fireball of a nuclear weapon appears to be a combination of ablation and insulation.[6] By ablation, we mean the removal of the insulating or protective material by melting and vaporizing, by sublimation and removal by a high gas velocity.

Heat shielding for industrial high-temperature processes can be provided by many different refractory materials, such as the carbides, nitrides, oxides, and sulfides of many elements. However, for high temperatures, such as are found in the fireball of nuclear weapons, these materials and all others quickly decompose into gaseous constituents. Ablation can absorb most of the heat received at the surface of the underlying structures and hence permit only a small portion of the incident energy to be stored in or pass to the solid of the structures.

The ablation rate depends on the rate of heat transfer to the surface and is influenced by the presence of products of ablation, their absorption of thermal radiation, the surface reflectivity of the protective coating, and the gas velocity across the surface. If the protective material is a chemical compound, it may dissociate after or during sublimation or evaporation and hence dissipate most of the heat transferred to the front face of the protective coating.[9] On the other hand, if the protective coating is a refractory metal such as tungsten, heat is produced in its oxidation. Experiments by Bloxsom[11] have shown that the heat of oxidation of the gaseous metal is not transferred to the solid surface, because the oxidation does not occur in the immediate vicinity of the surface.

Our study indicates that the exposed valves and entrance coverings can be protected from thermal destruction by means of heat shielding only by excessive thicknesses of single materials that utilize the process of ablation in combination with insulation.

THEORETICAL CONSIDERATIONS

Shielding by ablation is most effective if the shielding material has a relatively low sublimation temperature, a large heat of sublimation, and a sufficiently low thermal diffusivity, so that only a relatively small amount of the total heat is transferred to the shielding material and thus to the solid itself during a short exposure. It is desirable that the protective material have a low vaporization temperature to absorb the maximum amount of heat by ablation so that the temperature of the protected aluminum or steel may be kept below the melting point with a minimum thickness of shielding.

Georgiev, Hildago, and Adams[10] have shown that for satellite re-entry, the energy blocked by mass injection, i.e., the energy absorbed by the vapor as it diffuses across the boundary layer, is large in comparison with the latent heat of vaporization or the heat of sublimation. Teflon, for example, is found by these authors to have a heat of ablation five times greater than the heat of sublimation at the stagnation point heat-transfer rate for a typical satellite trajectory.

Shielding by sublimation at the surface of a solid, instead of melting and subsequent vaporization, is not only much simpler in analysis, but also avoids the instability of a liquid film. The simple theory used in the calculations for this study assumes a quasi-steady state; i.e., the rate of energy transfer across the surface is equal to the rate of energy absorption by ablation. After the temperature of the surface reaches the sublimation point, it remains approximately constant and provides a temperature gradient across the solid heat shield. If the sublimation temperature is high, the shield must have a coefficient of conductivity sufficiently low to keep the aluminum or steel well below its melting point.

The energy liberated in the explosion of a 10-megaton nuclear weapon (the size assumed for this study) is 10^{16} calories, of which approximately one third is thermal.[12] At a distance of 7,000 feet from the center of a surface burst the overpressure is about 100 psi; however, the maximum radius of the fireball is 11,200 feet. Calculations show that for a surface at this point, the Q received by any surface at a distance d with the fireball subtending an angle ϕ is:

$$Q = Q_o \frac{\pi}{2} \sin^2\phi$$

Where: Q = Energy received per cm^2

Q_o = Energy emitted per cm^2 for unit solid angle summed over all wavelengths at the surface of the fireball

This only holds for $\phi \leq 90^o$. After that, $Q = 2\pi Q_o$ because the object is engulfed by and is at the temperature of the fireball. The energy received has been calculated in cal per cm^2 sec. These calculations assume that the energy received per unit area near the edge of the fireball is the same as the energy emitted per unit area at its surface. The temperature at this location certainly is as high but may be higher than at the surface of the fireball. Also shielding may occur by energy-absorbing dust clouds. Consequently, these calculations represent an approximate value of the energy received per unit area. To our knowledge no measurements of Q_o have been made in this region of the fireball on any nuclear tests.

The Q received at a distance of 7,000 feet is plotted in Figure 3. Integration of this curve to 45 seconds shows that on a surface at a distance of 7,000 feet, the total Q received is about 60,500 cal per cm^2. Integration to 30 seconds, temperature = 3,680 C, yields 59,700 cal per cm^2.

If the weight of the shielding material per unit area is to be kept to a minimum it must have a large heat of ablation. A survey of the literature shows that carbon, carbides, and fluorocarbon resins can be adapted to the high-temperature shielding of aluminum and steel.[11] The calculations that follow illustrate the shielding properties of carbon and Teflon.

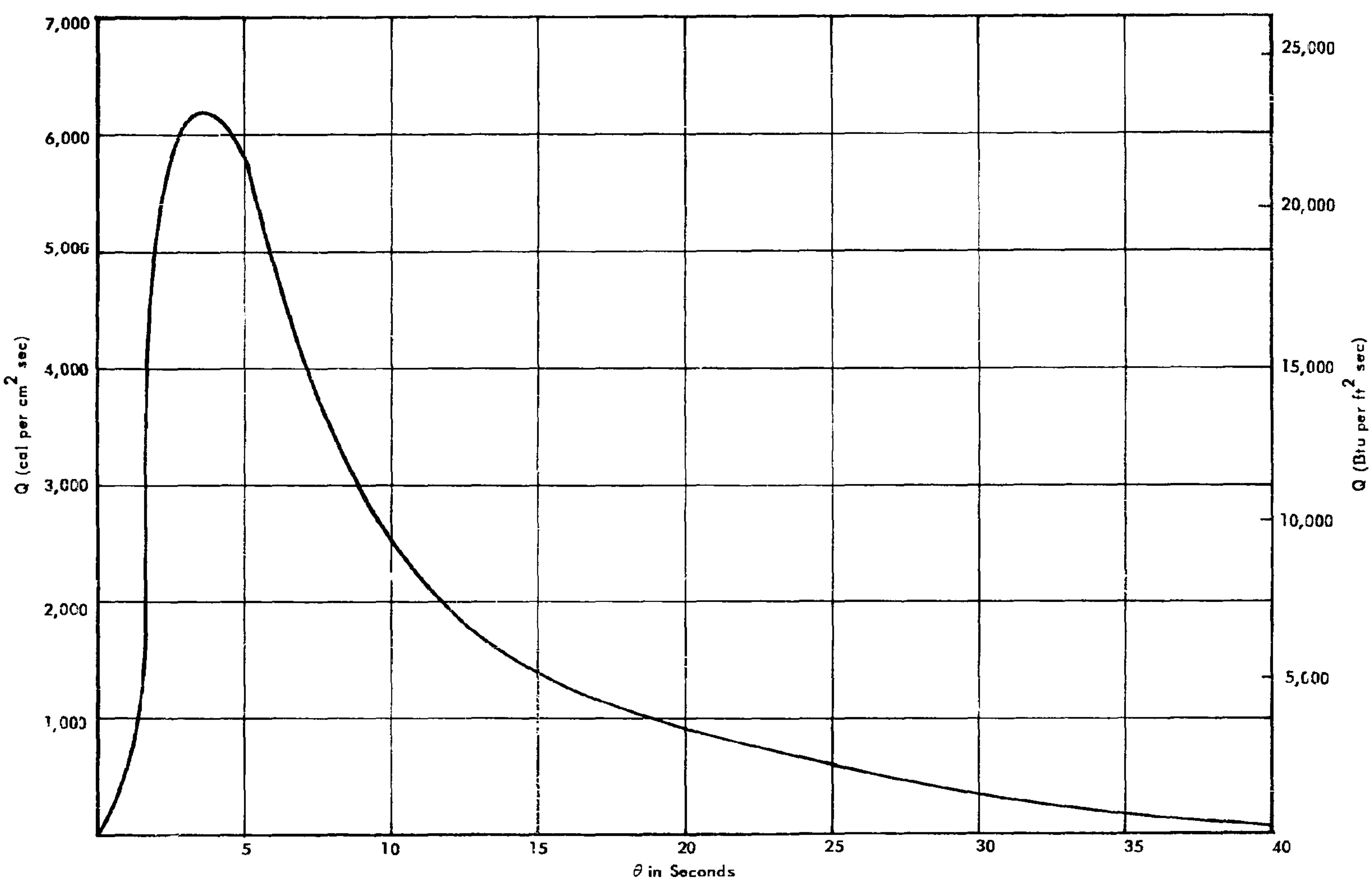

Figure 3. Thermal energy as a function of time for a 10-megaton surface burst.

CALCULATIONS — CARBON

Symbols and numerical values used in the equations:

C_p - Specific heat of carbon, 0.4 cal per gram*

d - Thickness in cm of carbon ablated

k - Coefficient of thermal conductivity, 0.25 cal per cm sec deg C*

m - Mass per cm^2 of carbon evaporated

Q_s - Heat of sublimation of carbon, 14,300 cal per gram*

T - Temperature in deg C at x cm from hot carbon surface after time, θ

T_o - Initial temperature of carbon, 20 C

T_s - Temperature at which sublimation of carbon occurs, 3,680 C

x - Thickness of carbon needed for insulation

α - Thermal diffusivity constant $= k/C_p\rho = 0.25\ cm^2$ per sec*

θ - Time in seconds for application of T_s to carbon surface

ρ - Specific gravity of carbon, 2.2 grams per cm^3*

In order to protect the blast closure valve, the temperature of the back of the aluminum cover (thickness, 7mm) should not exceed 700 F or 375 C. Graphite is ablated until the temperature of the fireball drops to 3,680 C, in about 30 seconds. The thickness of graphite ablated until θ = 30 seconds would be:

$$Q = m\,C_p\,(T_s - T_o) + m\,Q_s$$

$$59{,}700 = 0.4\ (3{,}680)\ m + 14{,}300\ m$$

* Data given by Bloxsom[11] and Litz[13] show that the thermal properties of carbon and graphite are affected greatly by the raw materials and fabrication procedures used in its production. Within limits the manufacturers of these products can and will adjust the properties of the finished product to specifications.

$$m = \frac{59,700}{15,800} = 3.78 \text{ grams}$$

$$d = \frac{3.78}{2.2} = 1.72 \text{ cm}$$

The temperature of the surface of the carbon is approximately constant during the ablation process (3,680 C). The back surface of the aluminum cover must not exceed 375 C during the 30-second exposure; accordingly, the front surface must not reach 446 C. The thickness of graphite to provide this insulation can be calculated by the following formula:[14]

$$T = T_s \operatorname{erfc} \frac{x}{2\sqrt{\alpha\,\theta}}$$

$$446 = 3,680 \operatorname{erfc} \frac{x}{2\sqrt{0.25\,(30)}} = 3,680 \operatorname{erfc} \frac{x}{5.5}$$

Therefore: $\operatorname{erfc} \frac{x}{5.5} = \frac{446}{3,680} = 0.121$

But: $\operatorname{erfc}(1.09) = 0.121$

Therefore: $\frac{x}{5.5} = 1.09$

$$x = 6 \text{ cm}$$

Hence: Total thickness needed $= d + x = 1.72 + 6.0 = 7.7$ cm

In these calculations, $\theta = 30$ seconds was assumed to be the time for the temperature of the fireball to drop below 3,625 C. Any shielding due to mass injection was neglected, so the thickness of 7.7 cm of graphite carbon represents an upper limit. However, what will happen to the graphite due to thermal shock with possible spalling and erosion at high temperatures is still unknown. The values of thermal flux at the maximum rate of delivery are 10 times those in any laboratory tests that have been performed.

Experimental checks on the efficiency of carbon as a heat shielding agent should be made. Other factors to be investigated are:

1. Oxidation of graphite

2. Resistance to thermal shock

3. Thermal expansion coefficient and mechanical strength

4. The use of pyrolytic graphite,[15] which has values of thermal conductivity differing by a factor of one to about 1,000 in different directions

CALCULATIONS — TEFLON (Polytetrafluoroethylene Resin)

Symbols and numerical values used in the equations:

C_p - Specific heat at constant pressure at 0 C, 0.223 cal per gram

d - Thickness in cm of Teflon ablated

k - Coefficient of thermal conductivity, 0.7×10^{-3} cal per cm sec deg C

m - Mass per cm^2 of Teflon evaporated

Q_{eff} - Effective heat of ablation, 2,200 cal per gram

T_o - Initial temperature of Teflon, 20 C

T_s - Maximum surface temperature, 640 C

x - Thickness of Teflon needed for insulation

α - Thermal diffusivity, $k/C_p\rho = 1.4 \times 10^{-3}$ cm^2 sec

θ - Time in seconds for application of T_s to Teflon surface

ρ - Specific gravity of Teflon, 2.1-2.2 grams per cm^3

The thickness of Teflon ablated would be:

$$Q = m\, C_p\, (T_s - T_o) + m\, Q_{eff}$$

$$60,500 = 0.223\ (640)\ m + 2,200\ m = (142 + 2,200)\ m$$

$$2,340\ m = 60,500$$

$$d = \frac{m}{\rho} = \frac{60,500}{(2.2)\ (2,340)} = 11.7\ \text{cm}$$

The temperature of the aluminum valve surface should not be greater than 446 C; therefore, an additional thickness of Teflon is needed, given by the following:

$$T = T_s\ \text{erfc} \frac{x}{2\ \sqrt{\alpha\,\theta}}$$

$$446 = 640\ \text{erfc} \frac{x}{2\ \sqrt{(0.0014)\ (30)}} = 640\ \text{erfc} \frac{x}{0.41}$$

Therefore: $\dfrac{446}{640} = 0.69 = \text{erfc}\ (2.44\, x)$

But: $\text{erfc}\ (0.28) = 0.69$

Therefore: $2.44x = 0.28$

$$x = 0.12 \text{ cm}$$

Hence: Total thickness needed = $d + x = 11.7 + 0.12 = 11.8$ cm

Neither of these calculations take into account the reflectivity of the carbon and Teflon or the possible cutting off of thermal radiation by gas escaping from the subliming surfaces.

DISCUSSION

Since nothing has ever been subjected to the environmental conditions calculated in this report except at full-scale weapons tests, it is difficult to know how materials will behave under these conditions. It appears from the simple calculations made that impractical thicknesses of single materials such as ordinary graphite or Teflon would be needed for protection. Built-up layers of anisotropic graphite, zirconium oxide, and aluminum oxide are being used in nose cones and rocket motors and appear to be much more attractive materials for thermal protection.[16,17] However, little or no data exists for such systems and each one is hand-tailored for the use of the system.

CONCLUSIONS

1. The exposed portions of underground 100-psi shelters must be protected against the thermal radiation from the explosion of megaton weapons.

2. This protection may be achieved by relatively thick coatings of carbon or Teflon.

3. Built-up systems of more sophisticated materials appear to offer a better solution to the problem.

4. A much more thorough analysis of such composite coatings is necessary and experimental tests of such coatings are needed before recommendations can be made for the optimum protection systems.

RECOMMENDATIONS

1. That suitable thermal-resistant protective devices be incorporated in the test plan if future megaton weapon tests are performed.

2. That laboratory tests of heat-shielding materials be made to develop the most suitable protective systems.

ACKNOWLEDGMENT

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